

## **Satellite-Derived Tropical Cyclone Intensities and Structure Change (TCS-08 and ITOP)**

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### **LONG-TERM GOALS**

To understand tropical cyclone (TC) structure and the time evolution from genesis to a mature storm while focusing on environmental conditions that impact rainband and inner core changes that are directly related to a TC's intensity and resultant wind and rain fields.

### **OBJECTIVES**

Develop accurate automated satellite-based techniques to estimate TC intensity and intensity changes under all conditions (e.g., 24 hr/day, any global location, and strengths ranging from tropical depression to Category 5). Create products that enable the TC community to monitor the three dimensional (3-D) TC environment (winds, moisture, and sea surface temperatures) and advance our ability to forecast TC intensity changes with a special emphasis on western Pacific (WPAC) typhoons.

### **APPROACH**

Satellite sensors represent the only observing platform that can currently provide the geographic coverage, and spatial, spectral, and temporal sampling required to monitor TC parameters in a near real-time mode. This project will focus on developing new satellite-based tools that assist the TC community in understanding TC structure changes by incorporating coincident recon data sets that can verify the fidelity of the satellite product suite, especially in the data poor (recon) WPAC region (Hawkins and Velden, 2011, Hawkins et al., 2010a, and Global Perspectives on Tropical Cyclones, 2009, Hawkins et al, 2009).

The Tropical Cyclone Structure (TCS-08, Harr et al, 2009) and Impact of Typhoons on the Ocean by Typhoons (ITOP - 2010) field programs provided unique aircraft reconnaissance (recon) data sets that will be used to validate a suite of satellite-based capabilities; a) TC intensity estimates, b) monitoring the time evolution of the 3-D environmental structure within and around TCs, and c) determining the inherent limitations of each method and potential way forward.

While Atlantic recon data has provided the only data to formulate these algorithms, WPAC data is sorely needed due to specific differences between TCs in both basins. Air Force WC-130J penetrations

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of the TC eye during TCS-08 and ITOP will be a key focus by incorporating dropsondes, Stepped Frequency Microwave Radiometer (SFMR) surface wind speeds, and flight level winds. The WC-130J derived minimum sea-level pressure (MSLP) and maximum sustained winds (Vmax) will form the basis for enhanced best-track values used to validate all satellite-derived intensity values.

Automated Dvorak Technique (ADT) intensities using IR data have been used operationally for multiple years, but suffer when a central dense overcast obscures vital storm structure (Hawkins and Velden, 2008). Microwave imagers, which can “see through” non-raining clouds, thus monitoring eyewall genesis, will be tested to see if they can add value to the ADT intensities until a clear eye permits the ADT to apply Dvorak “eye” rules. Our team will include the Cooperative Institute for Meteorological Satellite Studies (CIMSS, Chris Velden’s group) who have created the original ADT algorithms under NRL sponsorship and incorporated microwave eyewall structure information.

## WORK COMPLETED

1. Create automated center finding algorithm that can be applied to microwave imagery for the purpose of “centering” the image and then using the structural information to adjust the Automated Dvorak Technique (ADT) intensities to more accurate values.
2. Derive a microwave imagery only TC intensity module for inclusion in the satellite consensus (SATCON) estimate while incorporating automated center finding module
3. Create 1<sup>st</sup> SSMIS warm core anomaly intensity algorithm based on previous AMSU methodology using 2008-2009 recon data in Atlantic and Pacific.
4. Mapping air-sea interface environmental variables.

## TECHNICAL RESULTS

### *Section 1: Microwave Imager Data Utilization in TC Intensity Estimates*

Infrared-based (IR) Dvorak TC intensity estimates (whether manual or automated) suffer from upper-level cloud obscuration since key low and mid-level storm structure (rainbands and eyewall development) are frequently hidden or incompletely viewed. Microwave imager channels such as the ice scattering (85-91 GHz) and 37 GHz can provide key TC intensity details by their ability to “see through” non-raining clouds, thus mitigating the long standing disadvantages of IR-based methods. However, in order to routinely utilize microwave imager data in an automated manner, we must first devise a means to “center” the image with respect to the storm center, in order to appropriately comprehend the rainband and eyewall organization and temporal changes.

Our team has devised a technique we refer to as the Automated Regional Center Hurricane Eye Retrieval (ARCHER) to detect TC center positions, whether the input digital data is IR or microwave imager-based (Wimmers and Velden, 2010). After a storm location first guess is obtained, two processes are used to calculate quantitatively a storm center. Step 1 incorporates a “spiral score”:

$$SS(\phi, \theta) = c_{ss} \cdot N^{-1} \sum_{i \in \text{disk}} |\nabla \log(I_i) \times \mathbf{S}_i(\phi, \theta)|. \text{ SS} = \text{spiral score, the first term in the brackets is the}$$

gradient of the log of the image and  $\mathbf{S}_i$  is the spiral unit vector field center on a given latitude/longitude location  $(\phi, \theta)$ . In general, the idea is to search the brightness temperature ( $T_B$ ) imagery for large gradients that have organization around some centroid. Thus, a first guess is used to start the calculations, but this location can be displaced from the “true” center by 75-100 km and the algorithm will still work well. The spiral score is calculated at sample point (see Fig. 1) and then interpolated to the resolution of the image (contour plot). High values occur where the vector field lines up with the image gradients (associated with rainbands and eyewalls).

Ring scores  $RS(\phi, \theta) = c_{RS} N^{-1} \sum_{i \in \text{ring}} (-\nabla I_i \cdot \hat{\mathbf{r}}_i)$  are proportional the average dot product of the image

gradient and a radial unit vector on a ring and basically assess the existence and completeness of an eyewall feature. Ring scores are assigned to the center of a ring of points inside an eyewall. Fig. 2 highlights how the ring score is created when applied to the same ( $T_B$ ) image used in Fig. 1. ARCHER then combines the spiral and ring scores to create a “combined score” used to determine TC center locations:  $CS(\phi, \theta) = w_{SS} SS(\phi, \theta) + RS(\phi, \theta)$  where  $w_{SS}$  is the relative weight that depends on sensor type and generic storm intensity. The TC estimated center is the point at which the combined score reaches a maximum value. This end result is highlighted in Fig. 3 where the “first guess”, best track, and ARCHER values are all included for reference. Creation of an accurate, automated microwave imagery center finding technique is crucial in being able to a) analysis the contents of the microwave imagery for structure and structure changes, and b) can be used to aid the satellite analysts in their manual fix position efforts or potentially be used to provide these values unaided by human analysts and save time and effort.

ARCHER success has led to our team being able to deduce the presence and completeness of eyewalls and extract general information on storm intensity. Currently, if certain thresholds are exceeded, then the Automated Dvorak Technique (ADT) values are upgraded to a T# of 4.3 ( $> 72$  kts) or 5.0 ( $> 90$  kts). When compared with aircraft recon vortex messages in the Atlantic basin, these microwave-based adjustments are shown to provide value while ADT estimates are plateaued due to cloud obscuration. Fig. 4 demonstrates an example of how the additional of microwave imager data using these thresholds can mitigate IR limitations. Note how the initial plateau in IR-derived values at  $\sim 60$  kts is not seen in the ADT-MW algorithm. The ADT-MW (microwave) has been transitioned to 6.4 and is now in extensive testing with cases throughout the Atlantic, Pacific and Indian Ocean for feedback by the National Hurricane Center (NHC) and the Joint Typhoon Warning Center (JTWC) as well as for intercomparison with Atlantic recon vortex penetrations.

Our team has also made progress on extracting TC intensity values from passive microwave imager digital data sets. A machine learning algorithm has been developed that incorporates TC features mainly based on ice scattering (85 GHz) brightness temperature  $T_B$  digital data from the Special Sensor Microwave Imager (SSM/I). Derived products such as polarization corrected temperature (PCT), rainrate, and total precipitable water (TPW) were included while validating against Atlantic-basin aircraft reconnaissance vortex penetrations.

Our microwave intensity technique has added significant fidelity by adding both the 37 GHz data that details lower-level cloud liquid water and is less affected by shear aloft and convection near the center. In addition, we added a new feature that we borrowed from Dr. Richie’s genesis effort that incorporates

the gradient vector angles related to the image center using a 2 degree radius. This symmetry measure has become the top rated feature since it quickly recognizes the organization of the rainbands and eyewall or the lack thereof and basically does what the human eye does when visually scanning microwave images for patterns. The gradient vector method diagram is illustrated in Fig. 5.

When including: a) symmetry measure – based on the 2-deg radius gradient vector angles relation to center, b) average % encirclement of 1-km wide rings within 1-deg radius area (pixels < 253 K), c) difference in  $T_B$  of warmest center pixel and coldest surrounding pixel, d) sum of pixel  $T_b$  in the SE quadrant of the “eye” region, and e) average of the max  $T_b$  on each ring in the 1-degree radius area, plus other “features” we now have reached a root mean square error (RMSE) < 12.0 kts. This microwave imager only based method has now been transitioned to 6.4 for more extensive testing and inclusion of digital data sets from the Special Sensor Microwave Imager Sounder (SSMIS).

### *Section 3: Create SSMIS TC Intensity Algorithm*

SSMIS efforts to mirror the work accomplished by using the AMSU to monitor a storm’s upper level warm core temperature anomaly has now reached the viable stage since we have completed the first step in creating a matchup data base with coincident Atlantic recon vortex penetrations. The SSMIS channels are similar to the AMSU suite, but lack one mid troposphere channel. However, the SSMIS has the distinct advantage of being a conical instead of a cross track scanner, meaning spatial resolution is maintained across the entire swath. AMSU footprints increase in size as one nears the scan edge and AMSU intensity retrievals can NOT be carried out all the way to the swath edge due to the shear footprint size and its inability to adequately sample the warm core anomalies.

The SSMIS TC recon data base is now ~ 180 in size and we continue to enlarge the data set with Atlantic examples during the 2011 hurricane season. The existence of SSMIS on F-16, F-17, and F-18 has proven a boon to rapidly building the data base due in part to the 1700 km swath and the ability to have the inner core fall within any portion of the SSMIS swath. We have also included the matchups from the ONR sponsorship Guam-based field programs (TCS-08 and ITOP-10).

### *Section 4: Mapping Air-Sea Interface Environmental Variables*

Sea surface temperature (SST) mapping within the TC environment possess distinct issues for all IR-based remote sensing methods due to the abundance of clouds precluding a clear view of the sea surface below. Thus, microwave imagers are now being used to fill this void with varying success. During ITOP-10 Advanced Microwave Scanning Radiometer (AMSR-E) SSTs were provided in near real-time via NRL-MRY’s ITOP web page. Cold upwelled wakes associated with typhoons Malakas and Fanapi were readily apparent and this information directly assisted in planning the air dropped buoys that subsequently provided key surface and sub-surface measurements. Our team has since collaborated with the NRL-DC WindSat team and provides in Fig. 6 an additional example of how microwave imagers can map typhoon induced upwelling.

### *Section 5: High Altitude Genesis Sampling*

TCS-08 introduced a radical change in sampling genesis cases by incorporating the full suite of WC-130J capabilities: a) high altitude, b) long duration, c) dropsondes, d) airborne bathythermographs (AXBTs), and e) stepped frequency microwave radiometer (SFMR) wind speed mapping. These flights were carried out at ~30,000’ or 300 mb and enabled a much more complete 3-D mapping of the system’s temperature, moisture, and wind field for both scientific analysis as well as for coupled

modeling assimilation. TCS-08 cases revealed that many of these systems were suffering from a combination of wind shear aloft and dry air entrainment.

ITOP-10 genesis flights continued to enlighten us on the wide variety of vertical structure possible in WPAC potential genesis systems as highlighted in Fig. 7 and 8. Dropsonde winds at 400 mb show easterly winds are dominant and there is no hint of a circulation center aloft. However, Fig. 8 reveals that a vibrant low level circulation center (LLCC) and this vorticity center worked its way up to the mid- levels and aloft as illustrated in Fig. 9 when 400 mb winds map a closed circulation center. This system continued to evolve and become a typhoon shortly afterward. Information on the 3-D storm environment would not have become available without the high altitude WC-130J mission and bodes well for future missions as supplying initial conditions for coupled models becomes crucial in answering one of the main scientific quandaries for hurricane forecasting: how do we improve intensity forecasts.

## **IMPACT/APPLICATIONS**

The TCS-08 and ITOP (2010) field programs have provided valuable in-situ and remote sensing data set that will assist our satellite validation efforts on multiple fronts (TC intensity, surface wind fields, dry air intrusions, and storm shear). Our team has made progress on multiple fronts, especially on creating automated, accurate TC intensity techniques that are being transitioned to 6.4 work units that will carry new TC intensity algorithms to near real-time support and providing JTWC and the TC community with new insight on WPAC storm structure.

## **TRANSITIONS**

The ADT-MW module was transitioned to a PMW-120 6.4 project and used this past summer season by both the National Hurricane Center and the Joint Typhoon Warning Center (JTWC) for near real-time guidance. The microwave center finding method is now in 6.4 and being transitioned to NOAA for operational implementation next spring.

## **RELATED PROJECTS**

This project is closely related to a 6.4 effort sponsored by the Program Executive Office for C4I&Space/PMW-120 entitled “Tropical cyclone intensity and structure via multi-sensor combinations”, funded under PE 0603207N. The 6.4 project serves as the transition vehicle, works closely with JTWC and the National Hurricane Center and serves as the conduit to new products at FNMOC. Feedback from JTWC, NHC and the TC research community has been extremely positive in recent technical conferences.

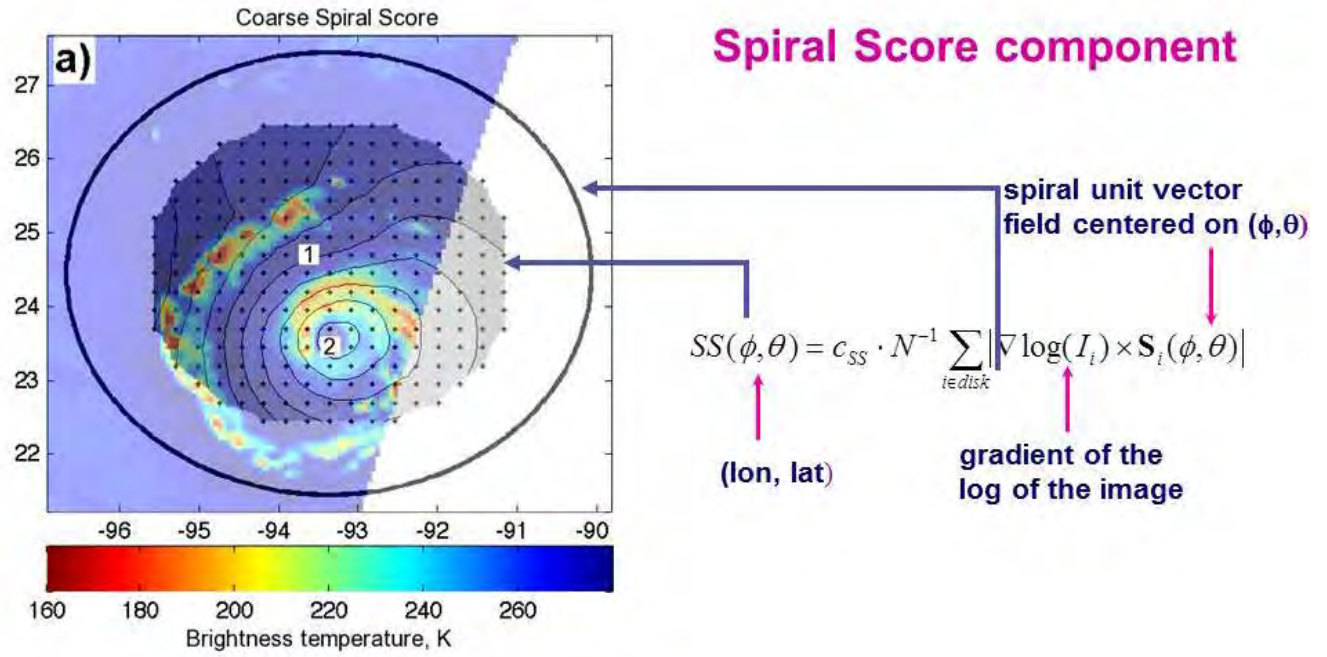
This project works closely with JTWC/NHC and FNMOC to understand the needs of the operational TC community via routine emails, phone calls and technical conferences (AMS, IHC, and TCC). Feedback is routinely solicited from all operational partners in order to understand how the 6.2 efforts outlined here can best be aligned to answer real world requirements and needs.

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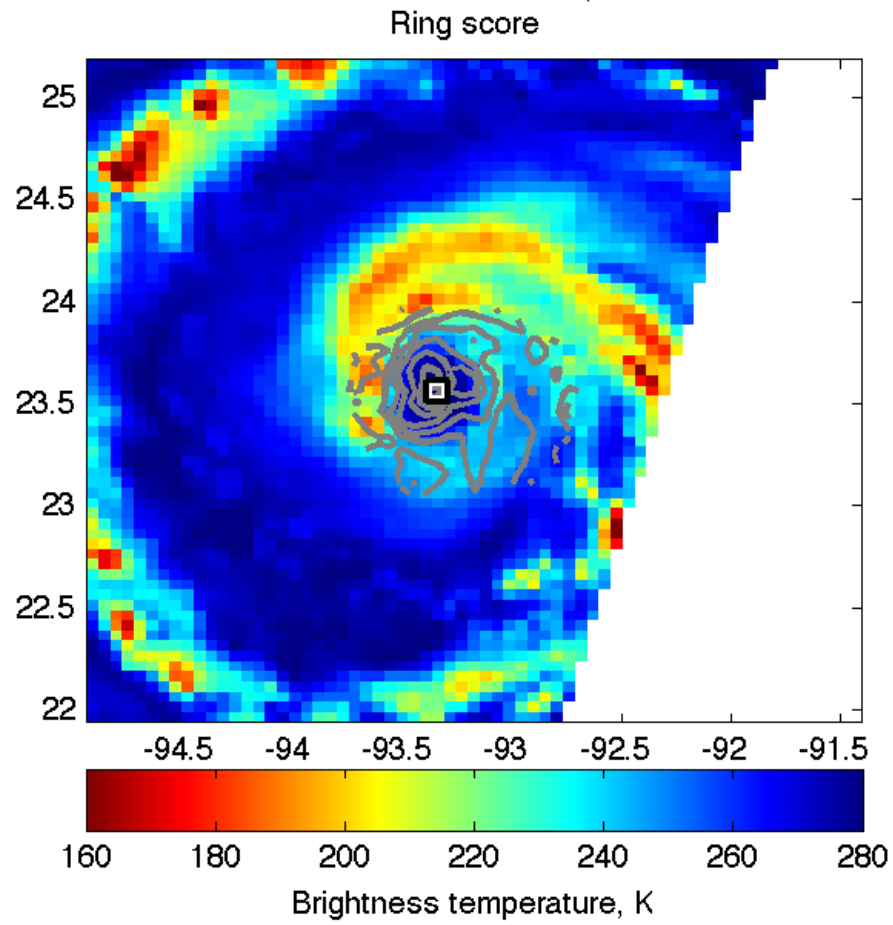
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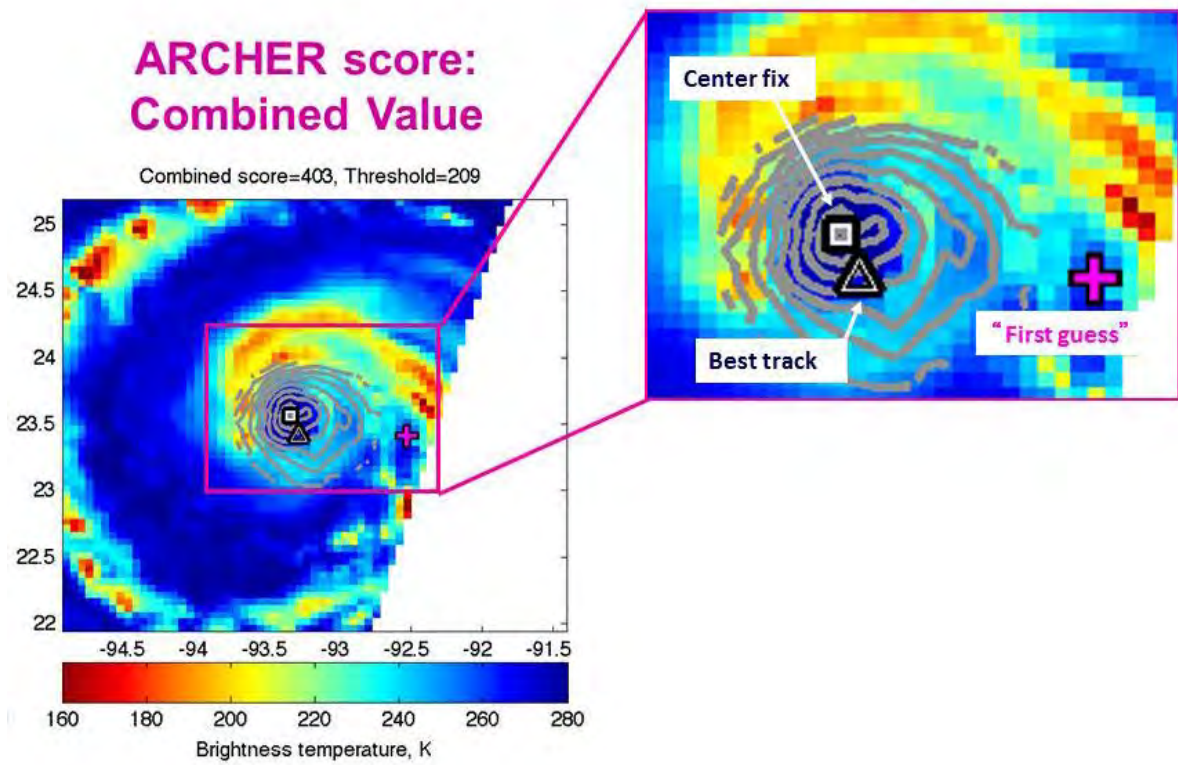


*Figure 1: Example of microwave imager brightness temperature image (ice scattering channel) with coarse spiral score technique applied (Courtesy Wimmers, CIMSS).*

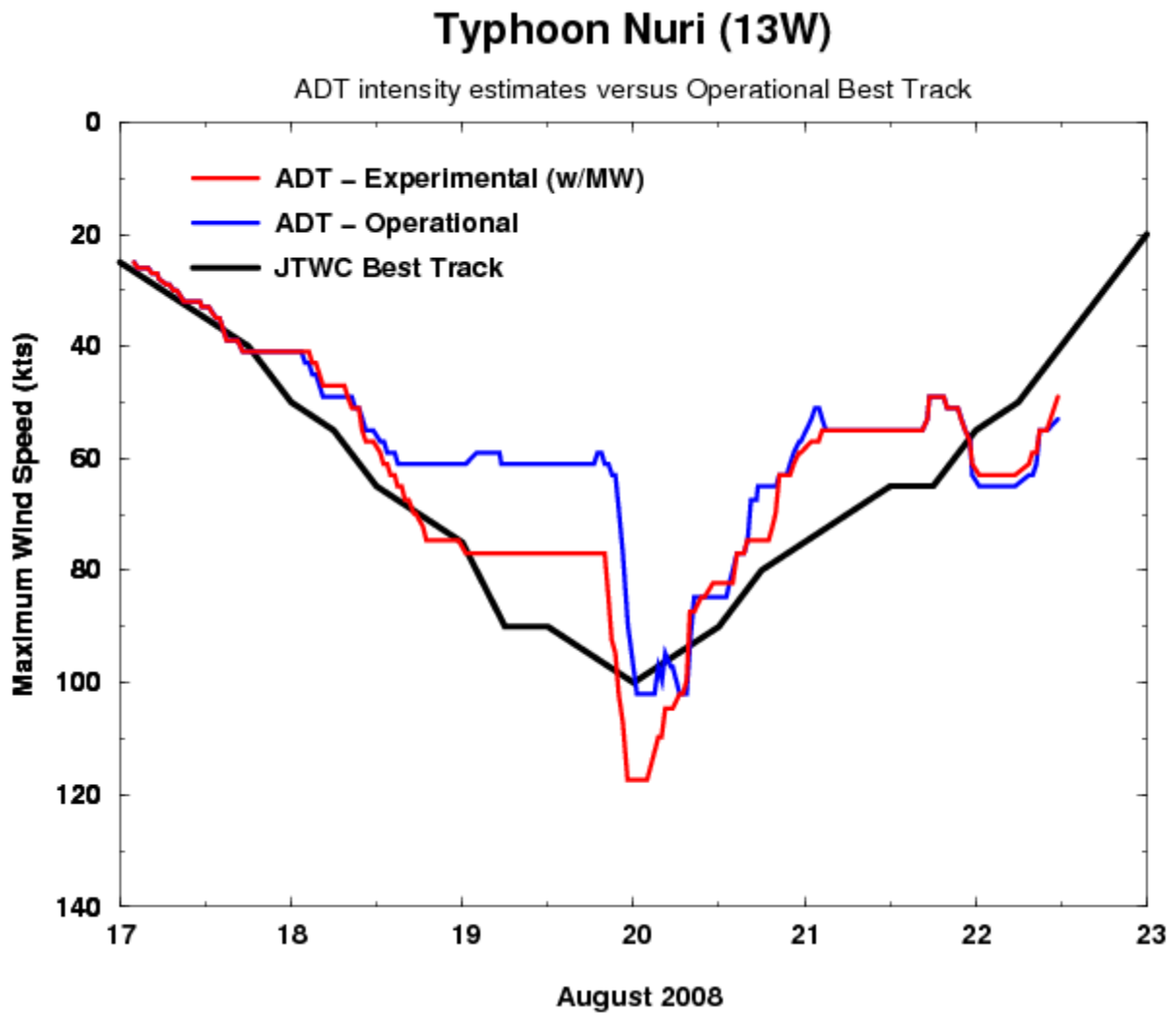




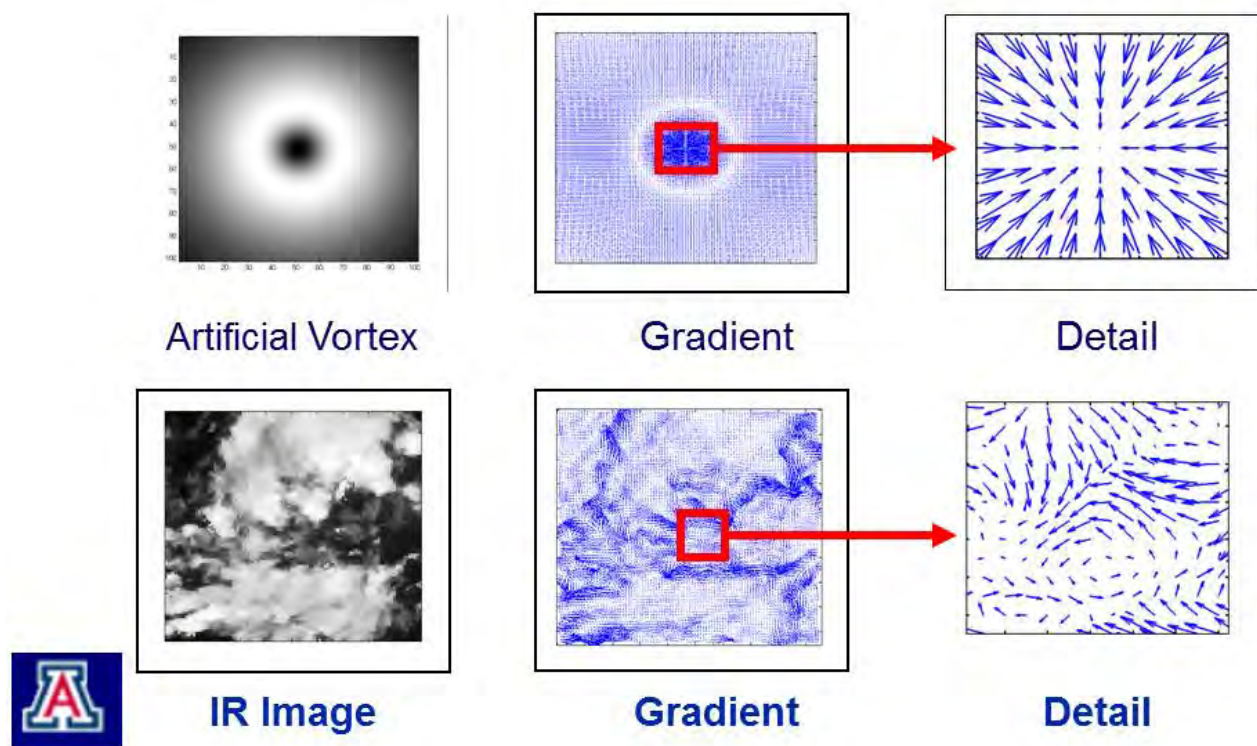
*Figure 2: Ring score for an ice scattering channel microwave imager brightness temperature image designed to assess the existence and completeness of tropical cyclone eyewalls.*



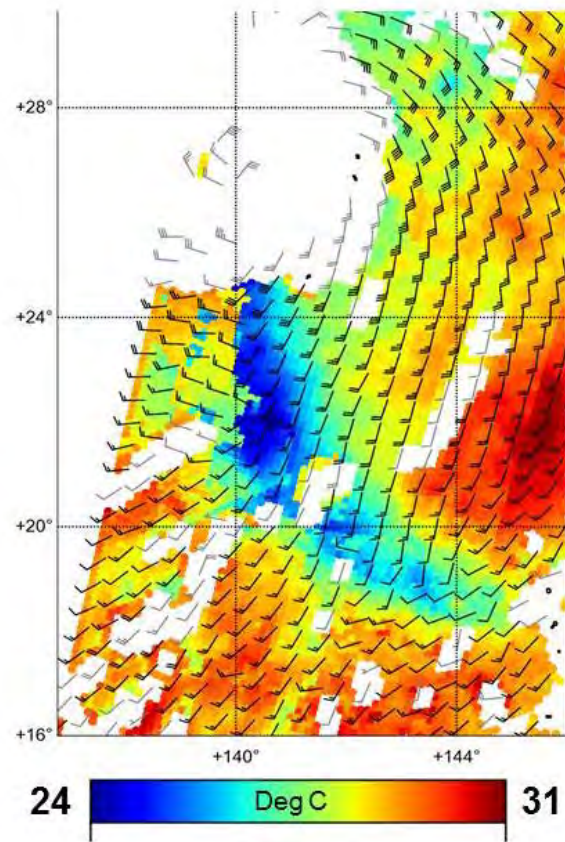
*Figure 3: ARCHER combined score (summing up the spiral and ring scores to determine via an objective method the best center location based on analysis of the microwave imager ice scattering channel image. The first guess (purple cross) and best track (black diamond) are included with the ARCHER derived center fix for intercomparison.*



*Figure 4. Example of ADT-MW (microwave) illustrating the benefits of eyewall structure analysis feasible with microwave imager data and how it can mitigate the ADT plateau shown in 13W to occur at ~ 60 kts. Black line – best track (JTWC), red line – ADT-MW, and blue line (ADT). This figure is from an associated 6.4 project, but is shown here for completeness.*

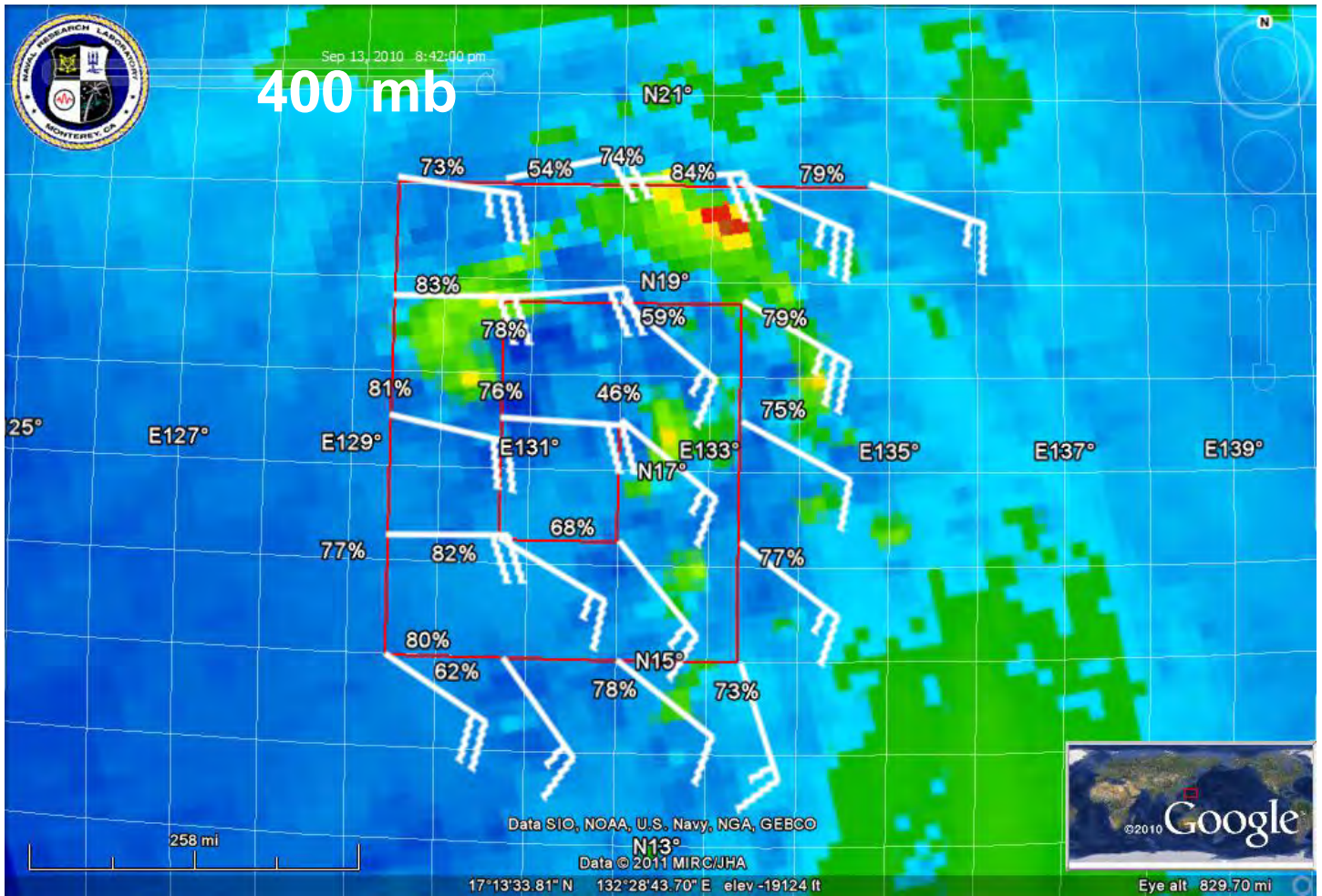


*Figure 5: Examples from Dr. Ritchie (U. of Arizona) on how the gradient vector calculation looks on a “perfect vortex” (top row) and when applied to a typical IR image of a tropical disturbance.*

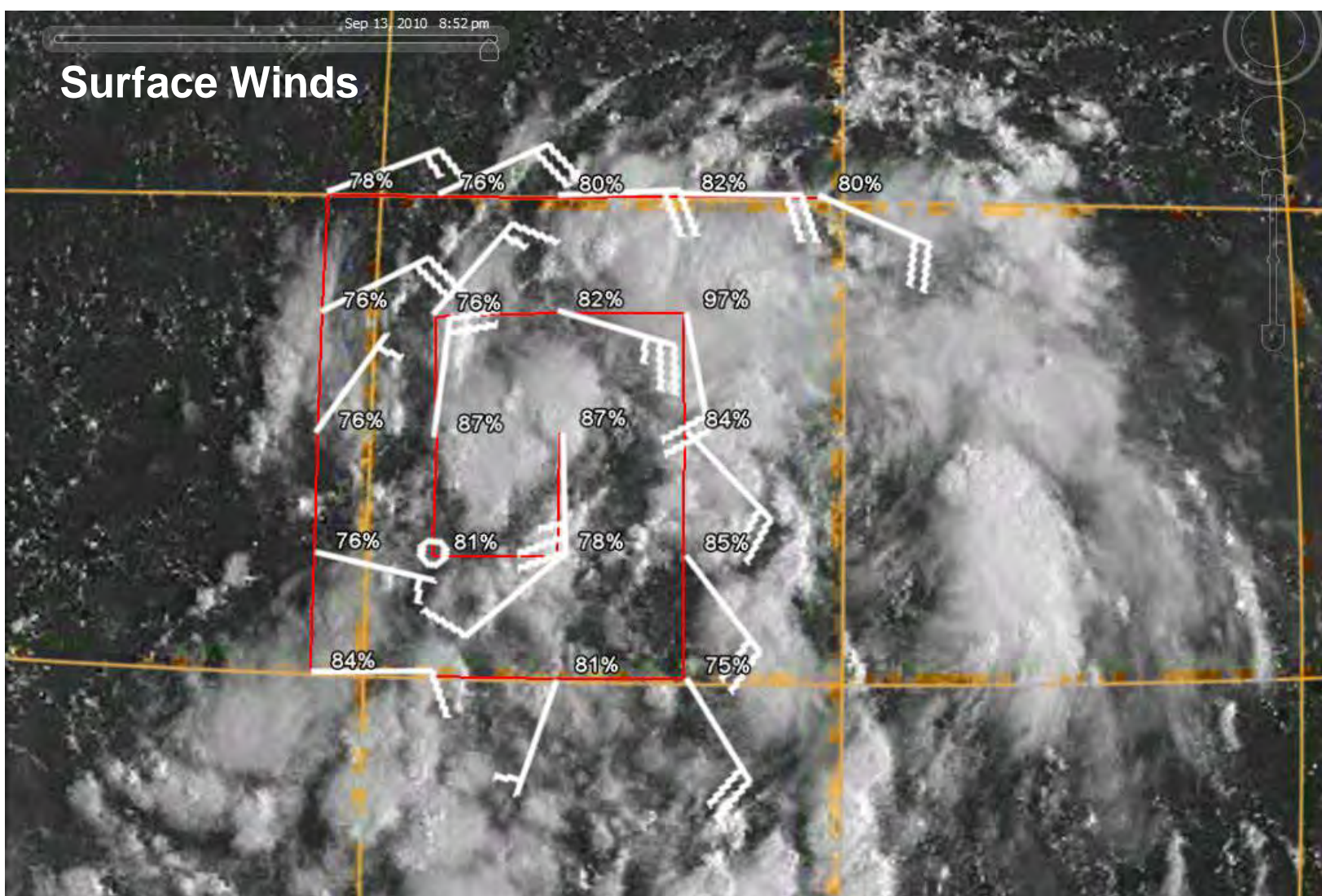


***Figure 6: SST upwelling (blue values) shown in the wake of typhoon Choi-Wan on Sept. 18, 2009 at 2038Z as demonstrated by the Coriolis WindSat microwave imager. Ocean surface wind vectors from the WindSat sensor are overlain. Note SST retrievals can NOT be made within heavy rain or inner core areas.***



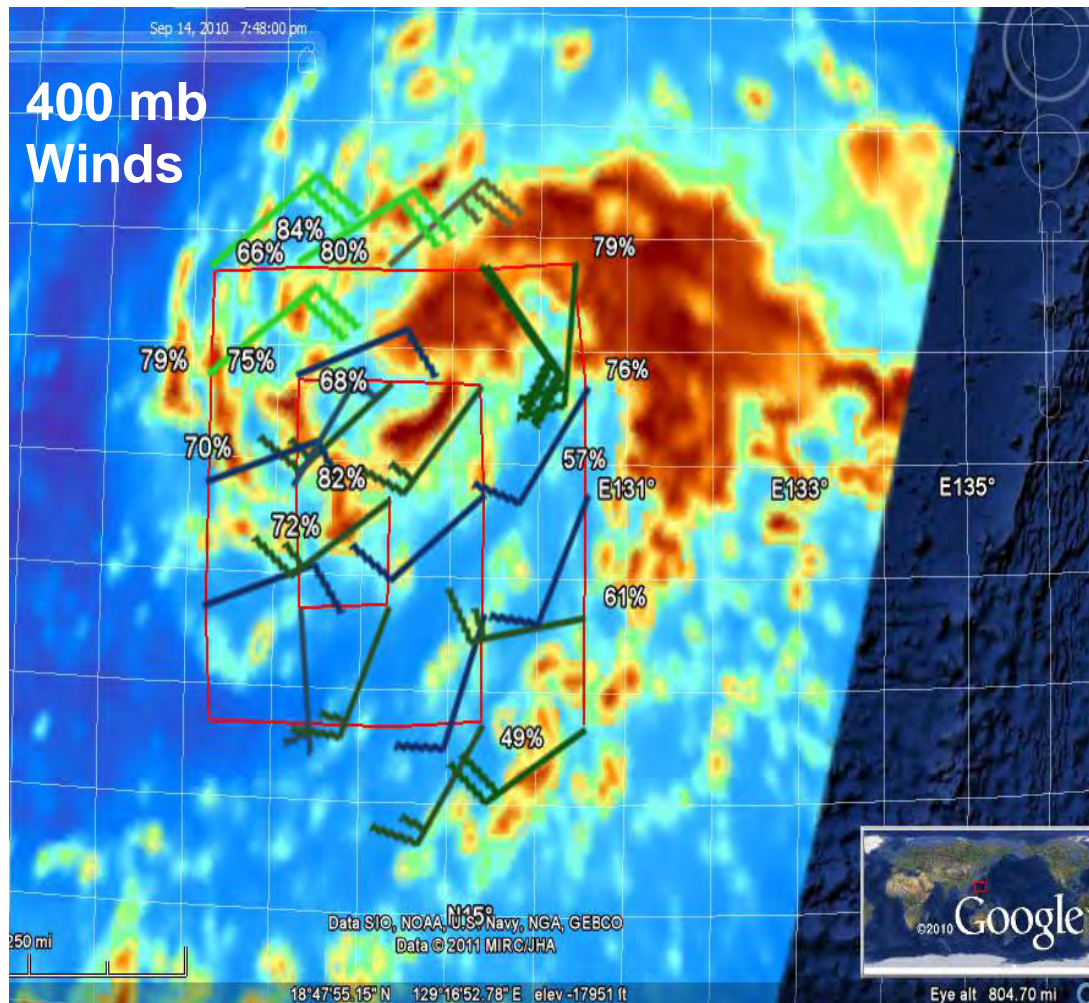


*Figure 7: 400 mb winds on Sept. 13, 2010 for a potential genesis system west of Guam during ITOP-10. The square spiral flight pattern was set up to encompass the mid-low level circulation center, but no closed circulation was evident aloft.*



*Figure 8: Surface level dropsonde winds from a Sept. 13, 2010 WC-130J flight into a potential genesis system west of Guam. The vorticity and low level circulation center shown here at the surface eventually works its way up and is present at 400 mb the next day.*





*Figure 9: 400 mb dropsonde winds overlain on WindSat 37 GHz brightness temperature imagery on Sept. 14, 2010, showing how the low level circulation is now evident aloft and the system has continued to develop.*